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TURBULENT PLASMA HEATING.(U)

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TURBULENT PLASMA HEATING

AFOSR Contract F49620-76-C-0014

Final Scientific Report

Period: July 1, 1976 to
September 30, 1979

John S. DeGroot
Principal Investigator

ABSTRACT

Results are presented for research funded under AFOSR contract F49620-76-C0014. This research involved measurements of plasma heating using electron beams, anomalous dc resistivity, and double layers. In addition, the development of a compact x-ray source is being investigated. An extensive set of measurements of the interactions of an electron beam with a collisionless plasma is summarized. It is found that the two stream electron wave decays into a large amplitude ion wave and an electron wave. The ion wave beats with the two stream electron wave and produces a short wavelength electron wave. This beat wave traps and heats the thermal electrons. The efficiency of conversion of beam energy to plasma energy is found to be less than one percent. Steady state anomalous dc resistivity has been investigated in a double plasma device. The spectra of the turbulence and the level of anomalous dc resistivity are in fair agreement with theory. We have constructed another device which will be used to investigate anomalous dc resistivity at much higher currents and electric fields. We have made preliminary measurements of very large amplitude double layer formation in another experiment. Finally, we are constructing a very high power gas puff z pinch. We will measure the time history of x-ray emission from this device.

1. Statement of Work

1.1 Beam-Plasma Heating

Measure the heated plasma energy distributions caused by electron beam excited electron-electron two stream instability both with and without ion turbulence. Measure the efficiency of conversion of beam energy to plasma energy.

1.2 Anomalous DC Resistivity

Measure the anomalous resistivity and heated plasma energy distributions due to the return current and a dc electric field.

1.3 Double Layers

Measure the heating efficiency of double layers and investigate the use of double layers to produce very intense electron beams.

1.4 Vacuum Spark-X-Ray Source

Measure the x-ray yield and the time dependence of the soft to hard x-ray intensity from a very fast, high energy vacuum spark.

2. Beam-Plasma Heating

We have made an extensive set of measurements[1,2] of the interaction of an electron beam with a collisionless plasma. We find that the two stream instability excited electron wave grows and saturates by trapping the electron beam as expected. The beam velocity is over an order of magnitude larger than the electron thermal velocity, and the beam density to plasma density is low enough so that the two stream electron wave does not trap the plasma electrons. Thus, our experiment is a model for a relativistic electron beam injected into a plasma. After saturation, the two stream electron wave decays into another electron wave and an ion wave. The decay ion wave beats with the two stream wave and produces a short wavelength electron wave by the off-resonant mode coupling mechanism suggested by Kruer[3]. The beat wave traps and heats thermal electrons. At low beam densities, a bi-Maxwellian thermal electron energy distribution is formed, but, at higher beam densities, a Maxwellian distribution is produced. Although the ratio of heated plasma energy density-to-beam energy density is as high as 8%, the efficiency of energy conversion from beam energy to plasma energy is much lower ($\simeq$ 0.6%). The point is that the efficiency of energy conversion is given by the rate of energy flow because the electron beam is injected into the plasma.

Thus, we have shown that the off-resonant mechanism does indeed result in significant plasma heating, but that the efficiency of conversion from beam energy to plasma energy is quite low.

3. Anomalous DC Resistivity

We have extneded the research reported[4] in the annual report for last year. We have made detailed measurements[5] of anomalous dc resistivity in a double plasma device. High density plasma is created in a large diameter (24") cylindrical chamber. Two high transparency screens separate this chamber from a small diameter (6") cylindrical chamber in which a low density plasma is formed. The large diameter chamber is biased so that a low energy electron beam is injected into the small diameter chamber. The density of the electron beam is comparable to the plasma density in the small diameter chamber. The cylindrical walls of the small chamber are biased to reflect electrons. Thus, all electrons in the small chamber must travel to the anode which is at the end opposite to the screens. Thus, the electrons in the small chamber are drifting with an energy of about the beam injection energy. We find that a virtual cathode is created close to the screens in the small diameter chamber. Thus, an electric field is applied to the plasma between the virtual cathode and the anode. We find[5] that, under certain conditions, large amplitude ($\delta n/n \lesssim 15\%$) ion acoustic waves are excited, and a strong anomalous resistivity develops. The resistivity agrees fairly well with the theoretical predictions of Sagdeev[6]. In addition, the wave spectrum is close to predictions[7] based on this theory. Thus, these measurements have verified some important aspects of the theroetical predictions. However, we find that anomalous resistivity only occurs for a narrow range of values of the applied electric field. The problem is apparently that space

charge limited flow limits the amount of current that can flow through the virtual cathode. The net result is that most of the applied electric field falls in the sheath region outside the plasma except for very special conditions.

We have constructed and tested a second device (STING) to be used to make measurements over a larger range of plasma currents and plasma densities. The STING vacuum chamber is a cylinder (diameter = 60 cm and length = 100 cm). A cylindrical tube (diameter = 8 cm and length = 30 cm) is aligned along the axis in the middle of the chamber. Plasma is created outside the tube. STING can be operated in one of two modes. In the first mode, plasma is only created at one end and a washer-shaped collar is placed at the entrance of the small tube so plasma is confined to only one end of the vacuum chamber. The anode is placed at the opposite end of the tube, and the tube is biased to reflect electrons. The point is that all electrons created in the large diameter chamber must transverse the tube. Thus, by adjusting the anode voltage and plasma density, a variable current can be driven in the plasma in the tube. Preliminary results indicate that large amplitude ion waves are excited in the tube. A transformer is used to apply an electromagnetic electric field to the plasma in the other mode of operation of STING. The transformer cores are ferrite toruses which are concentric with the axis of the tube. The plasma in the tube is the secondary of the transformer. In this way, we can apply very large electric fields ($E/E_R \lesssim 6 \times 10^4$).

Movable electrostatic energy analyzers are used to measure the spatial variation of the ion and electron energy distribution functions. Probes are used to measure the wave spectra as a function of space and angle and electron drift velocity. The experiment is controlled by a minicomputer which acquires and analyzes the data.

4. Double Layers

We have constructed and tested a device in which large amplitude ($e\Delta\phi/kT_e >> 1$) double layers can be formed. A magnetically confined, essentially fully ionized, plasma column is produced in argon gas by electrons emitted by a hot cathode and accelerated to energies of about 1 keV. To form the large amplitude double layers, a capacitor ($V_c \leq 5$ kW) is suddenly applied between the anode and the cathode. If the resulting current is large enough[8], then double layers should form in the plasma. Also, a density depression in the plasma reduces the required current. The double layer forms at the location of the density depression. In our experiment, Langmuir probes are used to measure the temporally and spatially dependent plasma potential, electron temperature, and electron density. An electrostatic energy analyzer is used to measure the ion energy distribution. We find[9] that if the density is too high ($n_e \gtrsim 10^{13}$ cm^{-3}), the plasma current just rings like an inductive discharge. However, at lower densities ($n_e \lesssim 10^{12}$ cm^{-3}), propagating double layers and anomalous dc resistivity are observed. These experiments are continuing with the objective of identifying the mechanism which drives the double layers and measuring the plasma heating efficiency.

5. Very High Power Z-Pinch-X-Ray Source

We are in the process of constructing a very high power z-pinch ($V \leq 100$ kV and $I \leq 3 \times 10^6$ A). This system is similar to Shiloh's experiment[10] in which gas is puffed into the anode-cathode gap and the voltage is applied suddenly. The gas density is controllable. We believe this solves the problems we found with the previous system, i.e., flooding the anode-cathode gap with material from the anode. The point is that without the gas puffed into the gap, the breakdown depends on material which is emitted by the anode. Our calculations[11] show that the x-ray emission from the plasma is a strong function of the plasma density. If the density is too high, the plasma stays relatively cold.

Our experiment will have a much higher voltage than Shiloh's (100 kV versus 30 kV) because Shiloh's results indicated that the yield of hard x-rays ($\geq$ 1keV) increased very rapidly with the applied voltage ($\sim V^5$). The time history of the soft to hard x-rays will be measured in our experiment.

6. Publications

6.1 Ph.D. Dissertations

1. H. M. Sze, Experimental Investigation of Moderate Energy Electron Beam-Plasma Interaction and Thermal Electron Heating with Finite Amplitude Ion Density Fluctuations, UCD PRG Report R-24 (1977).
2. W. M. Bollen, Experimental Investigation of Plasma Turbulence Driven by a High Density, Low Energy Electron Beam in a Double Plasma Device, UCD PRG Report R-39 (1979).

6.2 Abstracts

1. W. M. Bollen and J. S. DeGroot, Measurements of Anomalous DC Resistivity, B.A.P.S. 22, 1160 (1977).
2. W. M. Bollen, J. S. DeGroot, and C. Barnes, Measurements and Calculations of DC Resistivity, B.A.P.S. 23, 752 (1978).
3. E. W. Y. Ng and J. S. DeGroot, Experimental Investigation of the Formation and Propagation of Double Layers, B.A.P.S 23, 845 (1978).
4. W. M. Bollen, J. S. DeGroot, K. Mizuno, R. B. Spielman, and R. L. Walraven, Experimental Investigation of Current Driven Ion Acoustic Turbulence and Anomalous DC Resistivity, B.A.P.S. 24, 935 (1979).
5. E. W. Y. Ng and J. S. DeGroot, Measurements of the Formation and Propagation of Double Layers, B.A.P.S. 24. 960 (1979).

6.3 Reports

1. H. M. Sze and J. S. DeGroot, Measurements of Electron Beam-Plasma Interactions, UCD PRG Report R-26 (1977) and submitted to Phys. Fluids (1977).

2. W. M. Bollen and J. S. DeGroot, Experimental Investigation of Current Driven Ion Acoustic Turbulence, PRG Report R-43 (1980) and to be submitted to Phys. Fluids (1980).

7. Personnel Associated with Research Effort

J. S. DeGroot	Principal Investigator
A. J. Theiss	Investigator
H. M. Sze	Graduate Student then Investigator
W. M. Bollen	Graduate Student then Investigator
D. Horn	Graduate Student
E. W. Y. Ng	Graduate Student
K. S. Ray	Graduate Student

8. Degrees Awarded

1. H. M. Sze was awarded the Ph.D. degree in June, 1977. Thesis Title--"Experimental Investigation of Moderate Energy Electron Beam-Plasma Interaction and Thermal Electron Heating with Finite Amplitude Ion Density Fluctuations".
2. W. M. Bollen was awarded the Ph.D. degree in June, 1979. Thesis Title--"Experimental Investigation of Plasma Turbulence Driven by a High Density, Low Energy Electron Beam in a Double Plasma Device".

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1. H. M. Sze , Experimental Investigation of Moderate Energy Electron Beam-Plasma Interaction and Thermal Electron Heating with Finite Amplitude Ion Density Fluctuations, Ph.D. Dissertation, UCD PRG Report R-24 (1977).
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3. W. Kruer, Phys. Fluids 15, 2423 (1972).
4. J. S. DeGroot, Annual Scientific Report for AFOSR Contract F49620-76-C0014 for the period October 1, 1977, to September 30, 1978.
5. W. M. Bollen and J. S. DeGroot, Measurements of Anomalous DC Resistivity, abstract in B.A.P.S. 22, 1160 (1977); W. M. Bollen, J. S. DeGroot, and C. Barnes, Measurements and Calculations of Anomalous DC Resistivity in a Plasma, abstract in B.A.P.S. 23, 752 (1978); W. M. Bollen, Experimental Investigation of Plasma Turbulence Driven by a High Density, Low Energy Electron Beam in a Double Plasma Device, UCD PRG R-39 (1979) and Ph.D. thesis, Department of Applied Science, University of California, Davis; W. M. Bollen and J. S. DeGroot, Experimental Investigation of Current Driven Ion Acoustic Turbulence, UCD PRG Report R-43 (1978) and to be submitted to Phys. Fluids (1980).

6. R. Z. Sagdeev and A. A. Galeev, Nonlinear Plasma Theory (Benjamin, New York, 1969), pp. 94-103.

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9. E. W. Y. Ng and J. S. DeGroot, Experimental Investigation of the Formation and Propagation of Double Layers, abstract in B.A.P.S 23, 845 (1978); E. W. Y. Ng and J. S. DeGroot, Measurements of the Formation and Propagation of Double Layers, abstract in B.A.P.S 24, 960 (1979).

10. J. Shiloh and A. Fisher, High Density Z-Pinch, abstract in B.A.P.S. 20, 1298 (1975); J. Shiloh and A. Fisher, X-ray Spectra from a Gas-Puff Z-Pinch Plasma, abstract in B.A.P.S. 23, 848 (1978).

11. P. D. Nielsen, R. E. Stewart, and J. S. DeGroot, Dynamics of a High Current Z-Pinch, abstract in B.A.P.S. 24, 1037 (1979).

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